European Laboratory for Particle Physics

Large Hadron Collider Project **LHC Project Report 84**

Status of LEP2 and LHC

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Abstract

This paper discusses the status of the two colliders at CERN near Geneva, Switzerland. The electron-positron collider LEP2 now operates above the threshold for $W^{\pm}$ pair production. The Large Hadron Collider Project LHC, a proton-proton collider with a planned luminosity of 10 $nb^{-1}s^{-1}$ at a centre-of-mass energy of 14 TeV, is under construction and will be installed in the LEP tunnel.

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1 INTRODUCTION

This paper discusses the status of the two colliders at CERN near Geneva, Switzerland. The status of the electron-positron collider LEP2, operating above the threshold for $W^{\pm}$ pair production, is presented in Chapter 2. The status of the Large Hadron Collider Project LHC which is under construction and will be installed in the LEP tunnel, is presented in Chapter 3. The conclusions are in Chapter 4.

Table 1: Achieved 1996 LEP2 Parameters

Circumference C	26659	m
Maximum operating energy E	80.5	GeV
Number of bunch trains	4	
Number of bunches in a train	2	
Bunch spacing s	$118\lambda_{\mathrm{RF}}$	
Bunch radii $\sigma_x : \sigma_y$	300 : 3	μm
Maximum bunch current I	0.35	mA
Beam-beam tune shifts $\xi_x = \xi_y$	0.03	
Maximum luminosity L	30	$\mu b^{-1}s^{-1}$

2 STATUS OF LEP2

The electron-positron collider LEP has been operated at a beam energy of about 45.6 GeV, half the Z^0 mass, from 1989 to 1995. In June 1996, enough super-conducting RF cavities had been installed to to reach a beam energy of 80.5 GeV, exceeding the threshold of $W^{\pm}$ pair production. This phase of operation is called LEP2 [1].

2.1 Achieved 1996 LEP2 Parameters

Tab. 1 shows the list of achieved LEP2 parameters up to the end of the run in August 1996. The LEP2 circumference C is largest circumference of any storage ring in operation. The maximum beam energy is above the $W^{\pm}$ threshold, and determined by the amount of super-conducting RF system which was installed during the run from June to August and which I shall discuss in Section 2.4. We operate LEP2 with four trains of two bunches each. The spacing between the bunches in a train is $118\lambda_{\mathrm{RF}}$. In Section 2.2, I shall discuss how this is done. We have limits to the bunch and beam currents. The bunch current is limited at injection by the transverse mode coupling instability [2]. A second limit on the bunch current may be multi-bunch beam breakup in bunch trains [3], caused by wakefields, excited by earlier bunches in a train acting on later ones. The limits on the beam current are discussed in Section 2.4. Depending on the relative magnitude of these limits, we have different scenarios, including operating with individual bunches instead of bunch trains. The luminosity L follows from the currents and beam radii.

Fig. 1 shows the daily integrated luminosity with the left scale in nb^{-1}/d and the right scale in nb^{-1}/h. In the period from 28 June to 9 July we were running at the Z^0 for detector calibration. On 5 July we changed the lattice back to the 1995 lattice. On 9 July we made $W^{\pm}$ pairs. Up to 24 July we ran with four equidistant bunches, and till 16 August with four trains of two bunches each. The gap in luminosity is caused by a faulty septum magnet in the PS and by a machine development period of about a week.

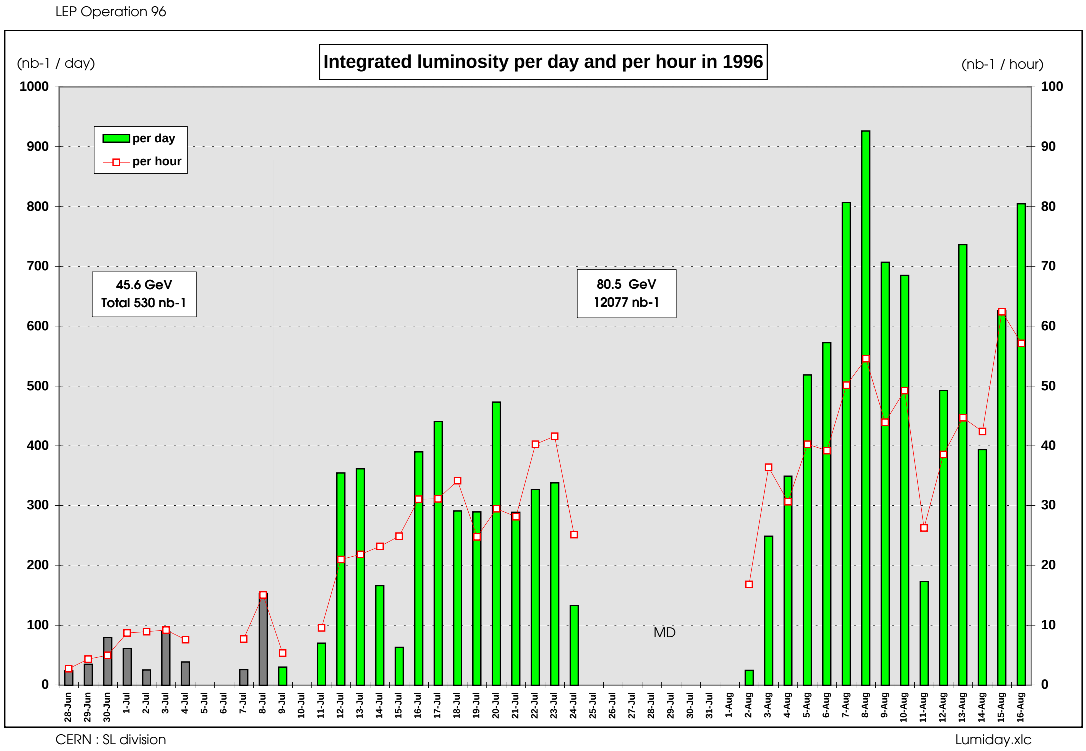

Figure 1: Daily LEP2 Luminosity 1996

2.2 Bunch Trains

Since LEP came into operation in 1989, the bunch current has been limited by transverse mode coupling instability. This predicted limit made us look for ways of increasing the number of bunches beyond four in each beam. In 1988, Rubbia [4] proposed to install a pretzel scheme in LEP, similar to that in CESR at Cornell University [5]. The number of bunches was severely limited by the LEP experiments, unless their electronics was rebuilt to take much shorter bunch spacings. LEP was operated with pretzels and eight bunches from 1992 to 1994. In 1990, Meller [6] proposed to replace the equidistant individual bunches in CESR by trains of bunches. In 1992, I made a proposal for LEP [7]. The bunches were to collide with a horizontal crossing angle and a concomitant horizontal offset in the super-conducting quadrupoles next to the interaction points. This scheme was dead by the end of 1993 because of the synchrotron radiation background from these quadrupoles [8]. Fortunately enough, Herr [9] proposed another scheme without a crossing angle and without an offset in the super-conducting quadrupoles in early 1994. LEP was running with one train in each beam, colliding in ALEPH and DELPHI by the end of 1994, and with four trains in each beam since 1995 [10].

Fig. 2 shows a typical bump in an even-numbered pit, where the two beams should collide head-on, and there should be no offset between them in the first quadrupole doublet from the interaction points IP. The logical place for the first electrostatic separator which launches the vertical separation bump between the two beams is behind the first quadrupole doublet where such separators already exist. The vertical orbit will then oscillate freely, crossing the vertical axis every half vertical betatron wavelength. A logical place to close the bump is in the neighbourhood of one of these zero crossings. We decided to install new separators near the seventh quadrupole QS7 from the IP, in order

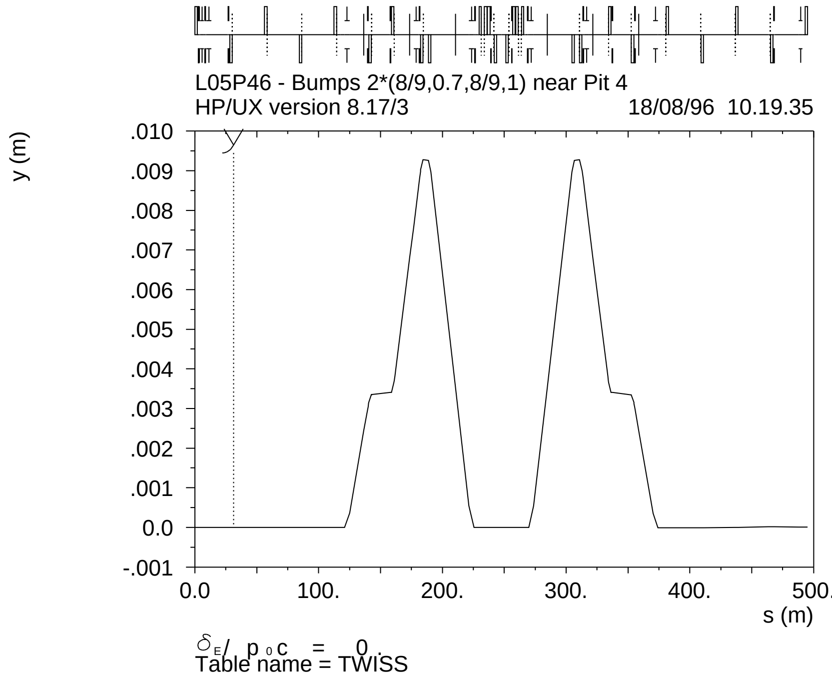

Figure 2: Bunch Train Bump near IP4. The interaction point is close to the centre of the abscissa. The diagram above the graph schematically shows the horizontally focusing (defocusing) quadrupoles as rectangles above (below) the axis, and the separating dipoles as centred rectangles. The curve is the vertical orbit y of the positron bunches at 45.6 GeV in collision.

to avoid vertical orbit offsets in the Cu cavities of the RF system. These offsets are one driving mechanism for synchro-betatron resonances. We use the existing separators near the fourth quadrupoles from the interaction points for closing the bumps. During injection and energy ramping, the beams are separated at the interaction points by not exciting the the separators behind the first quadrupole doublet.

2.3 LEP2 Lattice

The limit on the bunch current implies that the beam radii should become smaller as the beam energy increases, contrary to the natural behaviour, beam radii increasing like the energy, in a machine with a given lattice. In order to achieve the desired variation, we need lattices with smaller natural emittances than we have now, i.e. lattice with a higher horizontal phase advance and smaller dispersion than the lattices used in the past. Since 1992, we have been using a lattice with phase advances $\mu_x = 90°$ and $\mu_y = 60°$ in the arc cells. This year, we started with a lattice having $\mu_x = 108°$ and $\mu_y = 60°$. This lattice did not have enough dynamic aperture and we had to abandon it, returning to the lattice with $\mu_x = 90°$ and $\mu_y = 60°$. In parallel, another lattice with $\mu_x = 108°$ and $\mu_y = 90°$ has been developed [11] which in simulations has a better dynamic aperture than the abandoned lattice. Putting it into LEP is more difficult than it sounds at first sight, because it involves three day shifts of re-cabling the vertically focusing sextupoles. For the remainder of 1996, we foresee three weeks of running at $\mu_x = 90°$ and $\mu_y = 60°$, followed by the re-cabling, and another three weeks of running at $\mu_x = 108°$ and $\mu_y = 90°$.

2.4 Super-Conducting RF System in LEP2

By June 1996, enough super-conducting RF cavities had been installed to exceed the threshold of $W^{\pm}$ pair production. Tab. 2 shows the numbers of RF cavities, installed now and in the future. A total of 128 Cu cavities has been in LEP since the beginning. Eight of them were removed to make space for the pretzel separators. The first batch of super-conducting RF cavities was made of Nb sheet, the later batches of Cu sheet coated with a thin layer of Nb. The super-conducting RF cavities come in modules which are about 10 m long, contain 4 cavities, and deliver about 40 MV and 0.5 MW. The first line describes the situation between June 1996 and the beginning of the shutdown in August 1996. The second line shows the RF system that was installed in August and September 1996. In the shutdown from November 1996 to May 1997, we will start removing Cu cavities, and install more super-conducting ones, raising the energy to 94 GeV. In the shutdown from November 1997 to May 1998, we shall continue removing Cu cavities and complete the installation of super-conducting ones, raising the energy to 96 GeV. The cavity producting will be over in Spring 1997, and the module assembly in Summer 1997. Removing Cu cavities reduces the impedance of LEP, and should allow increasing the beam current.

Table 2: LEP2 Cavity Installation Schedule

Date	Cu	Nb	NbCu	GeV	Status
Jun 96	120	4	140	84	Installed
Oct 96	120	16	160	86	Installed
May 97	86	16	224	94	Approved
May 98	52	16	256	96	Approved

The super-conducting RF cavities reached their design field of 6 MV/m for the NbCu cavities and 5 MV/m for the Nb cavities [12]. So far, no deterioration of the cavities with time has been observed, which might have been caused by cryo-pumping on the cavity surfaces, by dust from opening and closing valves, and by the Nb layer peeling off. However, there were many trips of modules and of the RF power plant. Avoiding them requires improved diagnostics and controls which will be installed. We observe mechanical oscillations of the RF cavities at frequencies of about 100 Hz. They change the resonant frequency of the accelerating RF mode. If the cavity is tuned to the flank of the resonance curve, wild voltage oscillations occur. There are two causes of these mechanical vibrations: the cryogenic systems and the electro-magnetic forces, i.e. the vector product of surface current and magnetic field in the accelerating RF mode. The wild voltage oscillations are avoided by tuning the cavities on resonance, and accepting the increase in reflected RF power and in the RF power flowing through the couplers, and the reduction in efficiency.

2.5 LEP2 Performance Goals

The goal of LEP2 is accumulating an integrated luminosity of 500 pb^{-1} in three years. Tab. 3 shows the performance predictions for the last part of 1996, and for the years 1997 and 1998. The maximum beam energy increases as discussed before. We expect to run with four trains of two bunches each. More bunches are not useful because we reach the RF power limit with the eight bunches, if we can achieve the bunch currents listed.

Table 3: LEP2 Performance Goals

Year	1996	1997	1998
Maximum energy E/GeV	86	94	96
Bunch trains	4	4	4
Bunches in a train	2	2	2
Maximum bunch current I/mA	0.35	0.5	0.65
Peak luminosity $L/\mu b^{-1}s^{-1}$	50	70	110

We expect higher bunch currents in later years, because of the removal of Cu cavities. The last line shows the estimated peak luminosities.

3 STATUS OF LHC

The LHC project was approved by Council in December 1994. Big contracts start being placed. In September 1996, the Finance Committee approved contracts for the whole 50000 t of steel supply, the supervision of the civil engineering work, and eight magnet measuring benches. I assume for the remainder of the milestones that enough funds are available to construct the LHC in a single stage. By the end of 1999 most of the big contracts will have been placed, the prices will be known, and a final decision on the configuration can be taken. We assume that LEP will stop operation at the end of 1999. Continuing LEP operation into 2000 must be justified on scientific grounds and money must be found. Dismantling LEP will start in October 2000 when the civil engineering work for LHC is advanced such that it becomes necessary to break into the tunnel, in particular for the ATLAS and CMS caverns. Injection tests are foreseen from October 2003. Commissioning with beam will start in the second half of 2005. The latest conceptual design report [13] for the LHC was issued in October 1995.

3.1 LHC Parameters

Tab. 4 shows the LHC parameters. The circumference C is that of LEP, and known to even more digits than shown. The maximum energy E is a round figure, achieved at the dipole field B listed. The bunch spacing s corresponds to 10 RF wavelengths. Together with the distance from the interaction point IP to the separating dipoles it determines the number of parasitic collisions, about 15 on either side of the IP. The bunch population N and the bunch radii σ_x and σ_y are shown at the interaction point IP. They are adjusted such that the beam-beam tune shift parameter ξ falls into range believed to be achievable from experience with other hadron colliders which were or are in operation [14], and that the luminosity L is in a range which the experiments believe they can handle. The total beam-beam tune spread from the nearly head-on collisions and from all parasitic collision should be small enough to fit between nonlinear resonances of order up to twelve. Not all the space ℓ_Q between the IP and the front face of the nearest quadrupole is available to the experiments. At the assumed inelastic non-diffractive cross section $\sigma_{pp} = 60$ mb, the number of events in a single collision is $n_c = 19$.

3.2 Layout and Experiments

Fig. 3 shows the layout of the LHC. The pits are at the centres of the octants. The two LHC rings cross in Pits 1, 2, 5, and 8. The circumferences of the two rings are the same, since both rings have four inner and four outer arcs. The two large experiments, ATLAS and CMS, are diametrically opposite in Pits 1 and 5, respectively. Both are

Table 4: LHC Parameters

Circumference C	26659	m
Energy E	7	TeV
Dipole field B	8.4	T
Bunch spacing s	25	ns
Bunch population N	10^{11}	
Bunch radius $\sigma_x = \sigma_y$	16	μm
Bunch length σ_s	75	mm
Beam-beam parameter ξ	0.0034	
Luminosity L	10	$\text{nb}^{-1}\text{s}^{-1}$
Distance to nearest quadrupole ℓ_Q	± 23	m
Events/collision n_c	19	

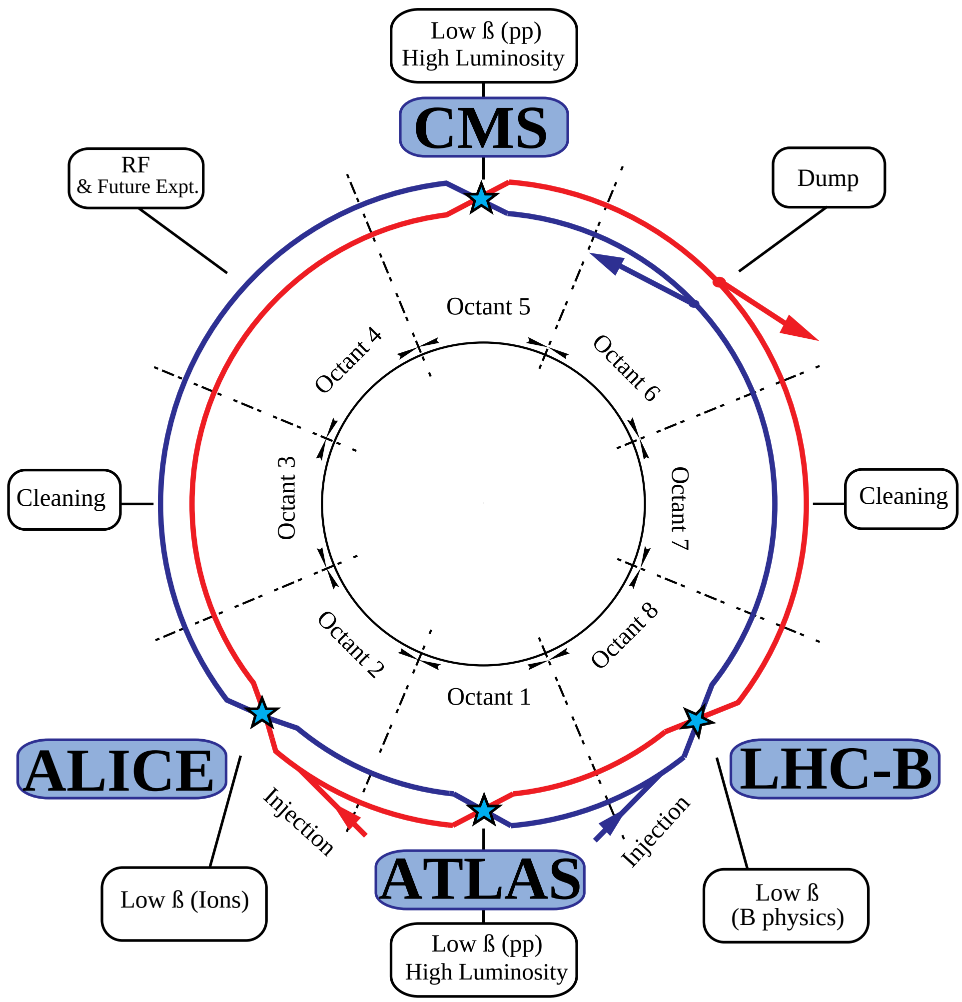

Figure 3: LHC Layout and Experiments

approved experiments with a cost ceiling of 475 MCHF each. Technical proposals were published in 1994 [15, 16]. The LHCC expects technical proposals for the subsystems. The heavy-ion experiment ALICE will be in Pit 2. The technical proposal for the core experiment [17] was published in 1995. The LHCC is waiting for the technical proposal for the muon arm. The LHC-B experiment is dedicated to the study of CP violation and other rare phenomena in the decay of Beauty particles. It uses colliding beams and a forward detector, contrary to the HERA-B experiment which uses a single beam and a gas jet target. A letter of intent [18] has been submitted to the LHCC. The LHCC wants an R&D programme for the detector. The two beams are injected into LHC into outer arcs upstream of Pits 2 and 8. The beam cleaning insertions to steer the beam halo into staggered sets of collimators rather than the super-conducting magnets are in Pits 3 and 7. Pit 4 houses the RF system. Pit 6 is reserved for the beam dumping system.

3.3 Layout and Optical Functions near Pit 5

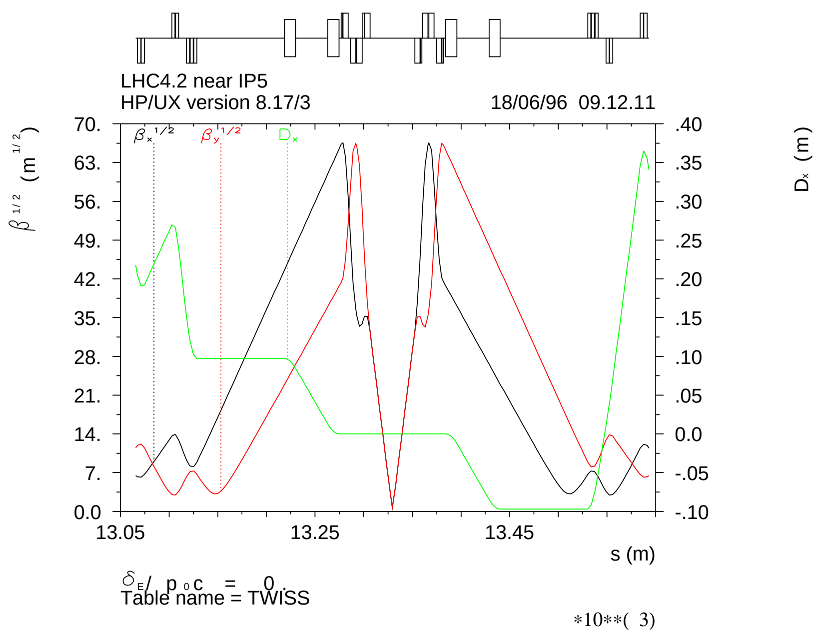

Figure 4: Layout and Optical Functions near Pit 5. The interaction point is close to the centre of the abscissa. The diagram above the graph schematically shows the horizontally focusing (defocusing) quadrupoles as rectangles above (below) the axis, and the separating dipoles as centred rectangles. The curves are the square roots of the horizontal and vertical amplitude functions in black and red and the horizontal dispersion in green.

The mimic diagram shows the LHC layout schematically over about 500 m in the neighbourhood of Pit 5. The low-β interaction point IP5 and CMS are close to the centre. On either side of IP5 is a quadrupole triplet, actually consisting of four quadrupoles. Because of the antisymmetry designed into LHC, the first quadrupole of the triplet focuses horizontally on the left, and defocuses on the right, and similarly for all other quadrupoles. The boxes behind the first triplet are the dipole magnets which first separate the two beams, and then make them parallel again at the correct distance of 194 mm at 1.9 K. Just before the dispersion suppressors there is a second triplet. The graph shows the optical functions $\sqrt{\beta_x}$ in black, and $\sqrt{\beta_y}$ in red. They are proportional to the horizontal and vertical beam radii. The antisymmetry of LHC makes them swap values when passing through IP5. Their values at IP5, $\beta_x = \beta_x = 0.5$ m, are too small to show clearly. Their maximum values in the first triplet are quite large. The green curve shows the horizontal dispersion D_x. It is matched to $D_x = D'_x = 0$ at IP5, and has asymmetric nonzero values behind the first separating dipoles.

3.4 Injection

The proton bunches for LHC are injected first into the PS booster which operates with just one bunch in each of the four rings. For this, the PS booster will be equipped with two new RF systems, one operating at $h = 1$ and the other at $h = 2$, superimposed such that the bunches are made longer and the direct Laslett space charge detuning is reduced. The four bunches from the four booster rings are injected into the PS. Then the PS booster cycles again, and another batch of four bunches is injected into the PS, and accelerated to 26 GeV. At that energy, the PS beam is adiabatically debunched, and captured by a new RF system, operating at $h = 84$ and 40 MHz. From this moment onwards, the bunches have the LHC bunch spacing of 25 ns. Three of these PS beams are successively injected into the SPS, filling only 3/11 of the SPS circumference, and accelerated by a new RF system at 80 MHz with a circumferential voltage of 0.7 MV to 450 GeV. Just before ejection towards the LHC, another new RF system at 400 MHz with a circumferential voltage of 6 MV is adiabatically turned on to match the SPS bunches to the LHC buckets. One such cycle takes about 16.8 s. Repeating this sequence twelve times fills one of the LHC rings, and takes about three minutes. The acceleration in the LHC from 450 GeV to 7 TeV takes about 20 minutes.

3.5 LHC Dipoles

The LHC dipoles occupy about 2/3 of the circumference. Fig. 5 shows their cross section [19]. The two apertures are in the same iron yoke and cryostat because the space in the tunnel does not allow two independent magnets and because a 2:1 design is cheaper. The space between the two apertures was increased from 180 to 194 mm in order to make their fields more independent and to reduce the collaring forces during their manufacture. Contrary to earlier designs, the cryogenic distribution line is no longer in the magnet cryostat. Only the cooling pipes with gaseous He at 50 K and 4.2 K for the intermediate heat shields, and the heat exchanger pipe at 1.9 K remain in the magnet cryostat. Its outer diameter was reduced to 914 mm. Cooling to this low temperature of 1.9 K is necessary to achieve the dipole field $B = 8.4$ T with super-conducting NbTi cable. The non-magnetic collars are made of aluminium. The field quality and its consequences for the LHC performance, in particular the dynamic aperture, are hotly debated between the magnet designers and my colleagues in accelerator physics [20].

So far, industry built seven and we tested six long dipole prototypes with 50 mm coil aperture and a length of 10 m, the nominal length when the orders were placed. The three best magnets, which had their first quench above 8.4 T and trained rapidly up to 9.6 T, are in the test string. The last one is being tested. Two prototypes with 56 mm coil aperture and the nominal magnetic length of 14.2 m are being constructed. The first magnet will be assembled in industry, the second at CERN, using collared coils produced in industry. The cold mass of the first of these magnets is expected in March 1997. Tests are foreseen in June 1997. A further four 10 m dipoles with 56 mm coil aperture are also in the pipeline, because the tooling for 10 m dipoles exists at several companies. In parallel

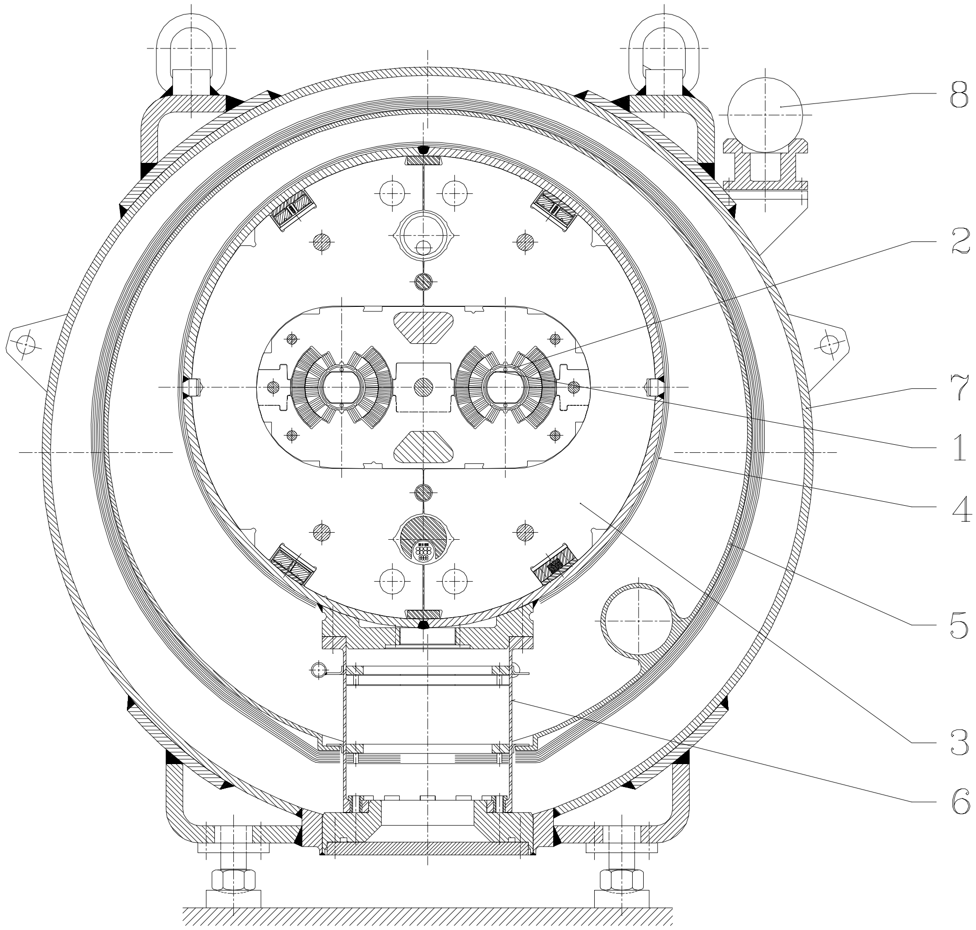

Figure 5: Cross Section of Dipole Magnet and Cryostat. 1. Beam screen, 2. Cold bore, 3. Cold mass at 1.9 K, 4. Radiative insulation, 5. Thermal shield at 55 to 75 K, 6. Support post, 7. Vacuum vessel, 8. Alignment target

to the long magnets, a programme of 1 m models is under way at CERN [21]. Its aim is studying the influence of individual coil parameters on the magnet behaviour with a fast turn around rate and qualifying possible design solutions. So far, eight single-aperture models were produced, at a rate of about one per month. The models tested so far show that at 2 K a field of 8.9 T can be reached for the first natural quench. Common to all models is a gradual training above this field level. A twin-aperture model with the same cross section as the long dipoles, now being fabricated in industry, will be completed and tested by the end of 1996. The cable insulation with polyimide tape was decided. Research and development programmes are under way on the super-conducting cable to increase the uniformity of the inter-strand contact resistance [22] and on current leads made of high T_c super-conductors [23, 24].

3.6 Vacuum Chamber

Fig. 6 shows one of the beam apertures. The coil aperture is now 56 mm. Just inside, still at 1.9 K, is the vacuum chamber with outer and inner diameters of 52 and 49 mm, respectively, made of stainless steel. Just inside the vacuum chamber is the beam screen which now has a racetrack shape with an inner horizontal diameter of 44 mm and a height of 36 mm. The purpose of the beam screen is absorbing the synchrotron radiation power, about 0.2 W/m from one nominal beam, at 5 to 20 K, using gaseous helium flow through the cooling pipes shown in Fig. 6, since the heat load at 1.9 K would be excessive. The beam screen is supported every 1.7 m. The synchrotron radiation photons will desorb gas molecules from the beam screen which will then be deposited on the screen by cryopumping. To avoid building up a gas layer on the beam screen, and deteriorating the vacuum, the beam screen has pumping slots in the straight top and bottom parts through which the desorbed gases can diffuse to the vacuum chamber walls where they are cryopumped again, but this time at 1.9 K where vapour pressure effects are negligible and the risk of being desorbed by the synchrotron radiation is absent. The electro-magnetic impedance of these slots has been the subject of intense studies [20, 25]. The beam screen is made of a high Mn content stainless steel to give a low magnetic permeability, and coated on the inside with 50 μm of copper in order to reduce its resistive impedance and associated heat load.

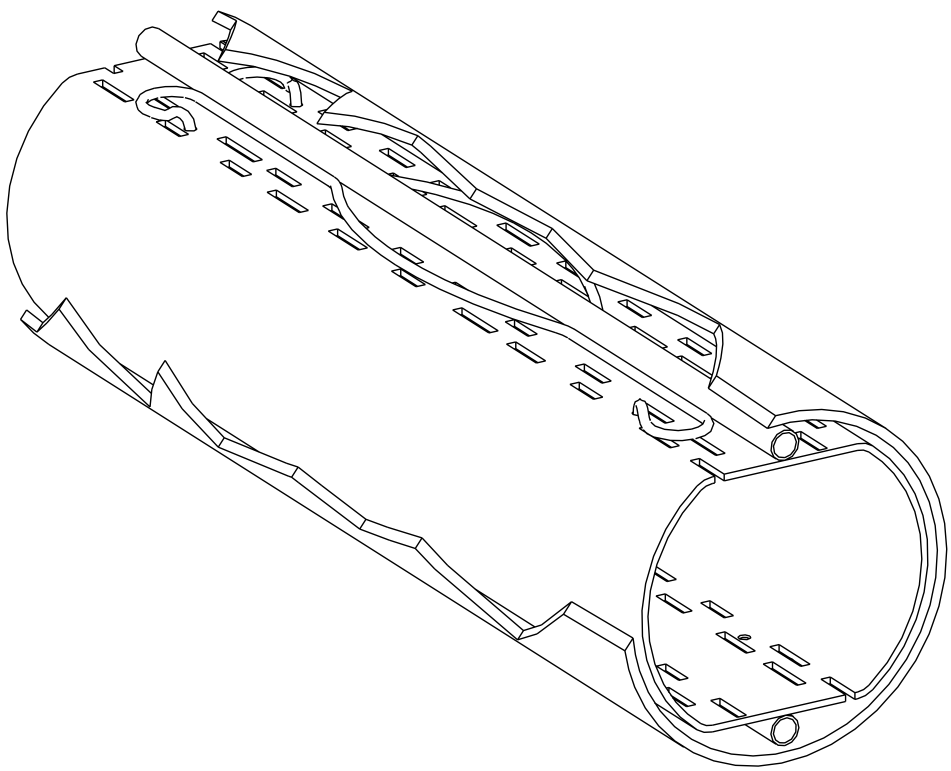

Figure 6: Cut-away drawing of the LHC vacuum chamber, perforated beam screen, cooling pipes and support springs.

3.7 Cryogenics

The super-conducting magnets are immersed in a bath of super-fluid He at 1.9 K, pressurised at about 1 bar. The heat is transferred by heat exchangers, consisting of a tube containing flowing saturated He II, and running through a half cell of the LHC arcs. It was checked in the string tests, that the liquid and gaseous He may flow in the *same* or in the *opposite* direction in this tube. The LHC tunnel is inclined with respect to the average vertical by at most 14.2 mr. Allowing He flow in either direction avoids the complication of changing the orientation of the cooling loop whenever the tunnel slope changes sign. Contrary to earlier designs, the cryogenic fluids are supplied by a separate cryogenics line which runs along the tunnel walls and is connected to the cryostats every half cell. The cryogenics supply line is fed from the four even pits where much equipment is available from LEP2 [26].

In collaboration with CEA in France, key technologies for high-capacity refrigeration at 1.8 K are being developed [27]. This includes very low pressure heat exchangers, cold volumetric and hydrodynamic compressors to be used as components of practical and efficient thermodynamic cycles. Prototypes of such machines from European industry were tested in the laboratory.

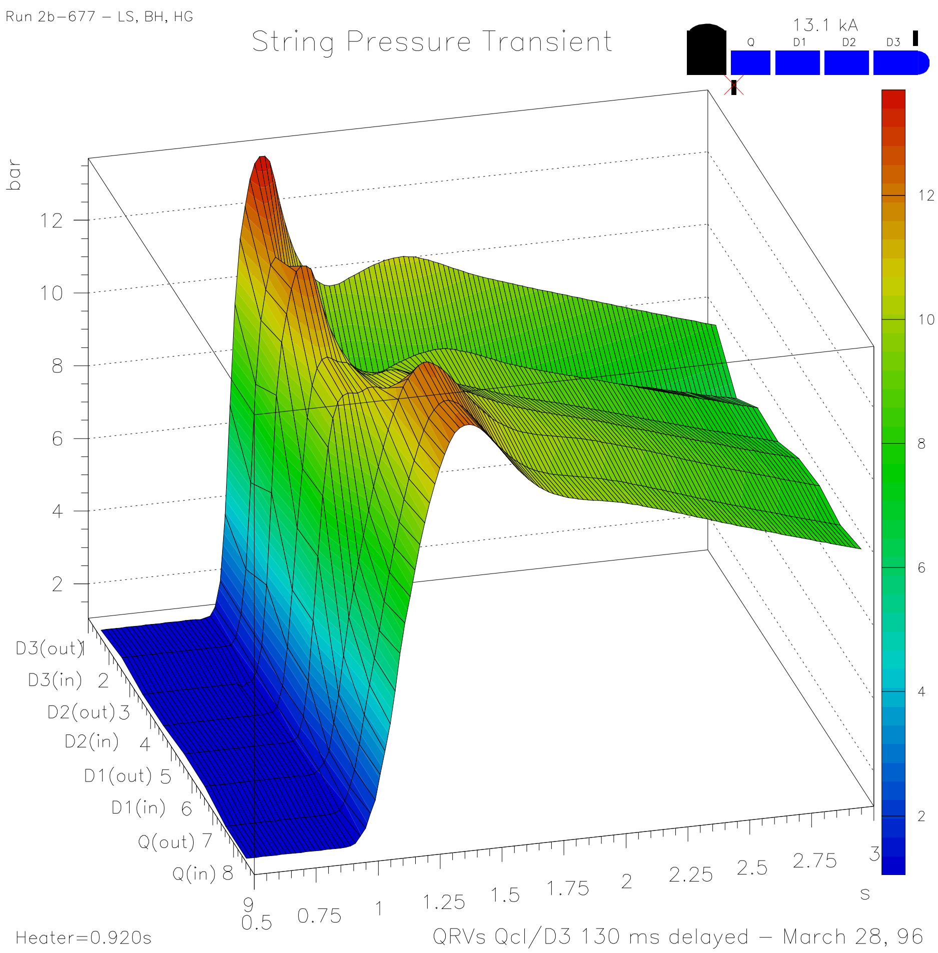

Figure 7: Pressure rise in dipole string tests during a quench. The right axis is the time in seconds. The left axis shows several points along the string. The ordinate is the pressure in bar.

3.8 Test String

The LHC test string [28] consists of a quadrupole of 3 m length and three dipoles of 10 m length each, the cryogenic equipment needed to supply the magnets with cryogenic fluids and gases, the cryogenic valves and short circuits for the electrical bus-bars, the power converters for the magnets, and control and diagnostic equipment. The test string has been in operation for two years, with more than 7500 hours at 1.8 K. It was cycled 2150 times, simulating several years of routine LHC operation. Its purpose is the experimental validation of the cryogenic cooling scheme and the development of the quench detection and magnet protection systems. The 1.8 K cooling with super-fluid helium was tested in steady state conditions and during transients. Much was learned on quench detection and magnet protection from the 20 natural and 64 provoked quenches so far; 35 of them occurred at or above the nominal field. In addition, there were about 15 quenches in the magnets *before* they were installed in the string. The temperature increases during ramping upwards at 10 A/s and downwards at 130 A/s were 6 mK and 50 mK, respectively, small enough not to quench the magnets. Simulating a heat load due to particle losses at 1 W/m caused temperature increases less than 30 mK.

The pressure rise during quenches was measured for various configurations of pressure relief valves, and for various delays in opening them. The observed pressure is shown in the graph. It remains less than 14 bar. Therefore the number of pressure relief valves was reduced from four to two in a half cell. The delays in opening the pressure relief valves are long enough that commercially available valves can be used. The string is installed on a slope simulating the slope of the tunnel. By swapping the string feed and string return boxes, flow of liquid and gaseous He in the same and opposite direction was tested, and both were found to be possible. This makes the layout of the cooling loops independent of the local slope of the tunnel.

3.9 New Civil Engineering

The civil engineering is concentrated around the interaction points. New caverns and access shafts are needed for the ATLAS and CMS experiments in Pits 1 and 5. The ATLAS cavern is so large that the CERN Main Building would fit into it. Less work is needed in Pits 2 and 8 where caverns and shafts already exist. New transfer tunnels are needed from the SPS to the LHC; TI2 for the clockwise and TI8 for the anti-clockwise beam, respectively. The transfer lines will be equipped with room temperature magnets. The tunnels for the beam dumps near Pit 6 are also new.

4 CONCLUSIONS

In LEP2, the installation of super-conducting RF cavities has continued as planned (cf. Tab. 2 since the Symposium, and a beam energy of 86 GeV has been reached. With the 90°/60° lattice, an integrated luminosity of 8.3 pb^{-1} was achieved in 17 scheduled days. Then the lattice was changed, as described in Section 2.3, to phase advances of 108° and 90°, and an integrated luminosity of 3.0 pb^{-1} was achieved in the remaining 10 scheduled days of the 1996 running period.

Since the publication of the Yellow Book [13] progress was made in many areas of the LHC design. There still are many ongoing studies of which I only mention a few. My colleagues in accelerator physics study the effects of the errors of the magnetic fields in the super-conducting magnets on the dynamic aperture, mostly by computer simulation, i.e. tracking [20]. These errors are caused by the arrangement of the coils, by fabrication tolerances, amplified by the 2:1 design, and by persistent currents at the injection field of only about 0.5 T. etc. We are also concerned about designing an LHC lattice which is robust enough to be operated with ease. Apart from the dipoles, other magnets need to be built. The insertion quadrupoles are particularly challenging, because the large beam size and the high sensitivity of the beam to their errors [29, 30, 31]. Studies of the super-conducting cable continue to find a cable which is mechanically stable and has a high and uniform inter-strand contact resistance [22].

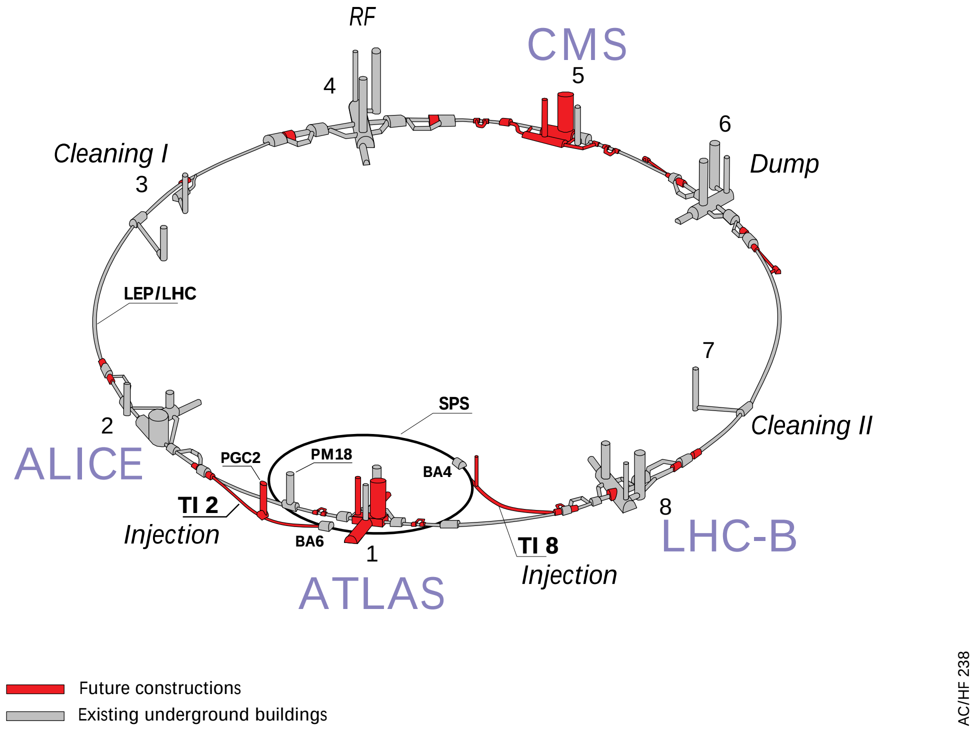

Figure 8: New Civil Engineering. The existing LEP tunnel, experimental halls and access shafts are shown in bright grey. The new experimental halls for ATLAS and CMS with their access shafts, the new transfer tunnels and the new beam dump tunnels are shown in red (or dark grey in the printed version).

Acknowledgement

This status report is based on the work of the very many people who are now working on the LEP2 and LHC projects.

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